



ON THE FLEXURAL AND LONGITUDINAL MODES OF THE CLASS 1 BARRELL-STAVE FLEXTENSIONAL TRANSDUCER

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Abstract

The piezoelectric Class I barrel-stave flextensional transducer is an underwater sound source that can be designed to have both flexural and longitudinal resonance modes below 10 kHz. While the fundamental flexural and longitudinal modes are usually well separated in frequency, the second flexural mode is often closely coupled to the longitudinal mode. In this article we examine the behaviour of these modes by varying the hoop stiffness and compliance of the aluminum staves that make up the primary radiating surface of the transducer.

Résumé

Le transducteur piézoélectrique flexensionnel à douves de classe I est une source sonore sous-marine qui peut être conçue afin d'obtenir des modes de résonance en flexion et longitudinaux à des fréquences inférieures à 10 kHz. Bien que les modes fondamentaux en flexion et longitudinal soient habituellement bien séparés en fréquence, le deuxième mode en flexion est souvent assez rapproché du mode longitudinal. Dans cet article, nous traiterons du comportement de ces modes en faisant varier la rigidité des cerceaux et la compliance des douves d'aluminium qui constituent la surface rayonnante première de ce transducteur.

Executive Summary

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Author:

Dennis F. Jones

Background:

Recent research into broadband transducers for active naval sonar systems has sparked a great deal of interest in the DREA Class III barrel-stave flextensional transducer. This unique underwater device uses coupled vibrational modes to generate sound efficiently over three octaves in the audio frequency band. Since the Class III transducer design is based on the narrowband Class I design, its performance is also affected by the modes in the latter transducer. Therefore, the frequencies of the flexural and longitudinal modes of the Class I barrel-stave flextensional transducer were the subject of this investigation.

Results:

The first part of this work was concerned with distinguishing between the fundamental flexural mode, the second flexural mode, and the longitudinal mode. It was shown that by increasing the hoop stiffness of the radiating staves using cork inserts, and by observing the resulting frequency shifts of the peaks in the response curve, one could identify the three modes. The second part of the work illustrated the effects of staff compliance on the frequencies of these modes by varying the thickness of the staves. We found that as the staff thickness increased, the frequencies of the fundamental and second flexural modes increased by 28% and 95%, respectively. The frequency of the longitudinal mode did not change significantly. Furthermore, it was shown that a crossover point existed where the second flexural and longitudinal mode frequencies were the same for a specific staff thickness. The importance of this crossover point to the successful design of a broadband Class III barrel-stave flextensional transducer was discussed.

Significance:

The results of this study have been incorporated into the most recent version of the broadband Class III barrel-stave flextensional transducer.

Future Plans:

All future work will focus on improving the broadband Class III transducer design.

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1. Introduction

The barrel-stave flextensional transducer was conceived in 1986 at the Defence Research Establishment Atlantic (DREA) and patents were granted in Canada and the United States in the early 1990s [1]. Many versions of this compact underwater sound source were developed for use in naval sonar applications [2]. Some of them were commercialized through technology transfers to Canadian industry [3] and subsequently integrated into sea-going systems like the Australian Sonar Research Projector towbody [4]. Today, these transducers are being used in such diverse fields as acoustic underwater communications, ocean acoustic tomography, and marine mammal acoustics.

Brigham and Royster conveniently grouped a number of flextensional transducer designs into a simple morphologically-based classification scheme in the late 1960s [5, 6]. Their original five classes were supplemented with two further classes by Rynne [7] in 1992. Three years later, Jones et al. [8, 9] added three types of barrel-stave flextensional transducers to the classification scheme. A review of all seven classes, including measured performance parameters for experimental and/or commercial transducers belonging to each class, was published for the first time in 1995 by Jones and Lindberg [10].

Recent interest in broadband underwater sound systems has focussed a great deal of attention on the Class III barrel-stave flextensional transducer [11-13]. This transducer achieves broadband status through close coupling of flexural and longitudinal modes of vibration. Since the Class III transducer is basically an end-to-end graft of two Class I barrel-stave flextensional transducers, the modes of the latter are critical to the design of the former. Consequently, the resonance frequencies of the flexural and longitudinal modes of the water-loaded Class I barrel-stave transducer were examined in this work.

2. Transducer Description

The Class I barrel-stave flextensional transducer consists of an internal piezoelectric ceramic driver surrounded by a set of concave aluminum staves as shown in Fig. 1. The driver is a segmented stack of ten Navy Type I lead zirconate titanate (PZT) rings connected in parallel electrically. Each ring has an outside diameter of 5.07 cm, a wall thickness of 5.6 mm, and a height of 1.02 cm.

Two steel end plates having octagonal cross-sections are glued to the ends of the driver and support eight curved staves that are bonded and bolted in place. The end plates are 2.99 cm on each side and 1.27 cm in height. The aluminum staves are 12.7 cm long with a maximum thickness of 6.35 mm and a radius of curvature of 20.0 cm. Aluminum end caps and a stainless steel tie bolt are used to maintain compressive bias on the ceramic stack. The end caps have a 5.08 cm outside diameter and a 1.27 cm height. The tie bolt has a diameter of 6.35 mm.

A rubber boot (not shown in Fig. 1) seals the transducer from water ingress through the gaps between the staves. The gaps are approximately 1 mm in width and the boot is 1 mm thick prior to stretching over the transducer.

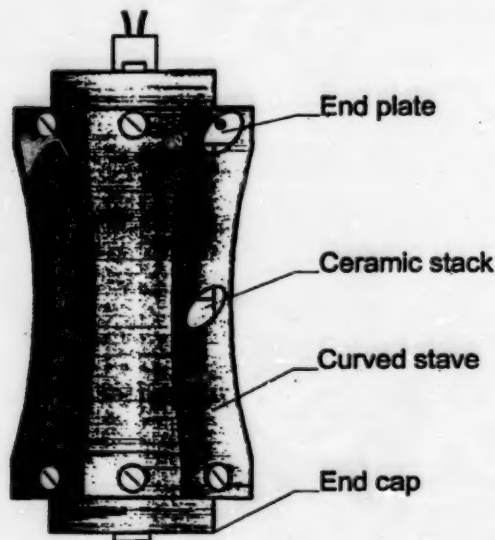


Figure 1: Class I barrel-stave flextensional transducer.

3. Hoop Stiffness Effects

One method that can be used to distinguish between the flexural and longitudinal modes of the water-loaded barrel-stave transducer is to slightly increase the hoop stiffness of the staves. This will increase the resonance frequencies of the flexural modes, which depend on the geometry and properties of the staves, but will leave the resonance frequency of the longitudinal mode essentially unchanged since this mode is primarily influenced by the properties of the driver and end plates.

A simple way to increase the hoop stiffness of the staves is to fill the gaps with an elastic material that has a low Young's modulus (E) and density (ρ) compared to those of aluminum. A suitable material is cork, whose properties are given in Table 1. Since 1 mm thick cork sheets are commercially available, they are ideal for this investigation since they match the width of the gaps between the staves. As an added bonus, the low Poisson's ratio (ν) for cork means that the shear stresses on the adhesive holding the cork in place will be low.

Table 1: Material properties.

Material	E (GPa)	ν	ρ (kg/m ³)
Aluminum ¹	71.7	0.32	2800
Cork ²	0.01	0.05	240

¹Property data from Refs. 14 and 15.

²Property data from Refs. 16 and 17.

During the assembly of the barrel-stave transducer, cork was inserted between each pair of adjacent staves and bonded in place. The transducer was then sealed with a neoprene coating and tested at a depth of 14.7 m in seawater at the DREA Acoustic Calibration Facility on Bedford Basin. Subsequently, the cork inserts and neoprene were removed and the transducer was fitted with a rubber boot then re-tested at the same depth. The transmitting voltage response (TVR) curves for the transducer with and without cork inserts are shown in Fig. 2.

With the cork inserts in place, there are only two resonance peaks in the TVR curve below 10 kHz. The first occurs at 2.69 kHz and can be identified as the fundamental resonance mode. The second peak occurs at 7.60 kHz and corresponds to the longitudinal resonance mode.

Without cork inserts, the barrel-stave flextensional transducer operates normally with three resonance peaks in the frequency range below 10 kHz. The resonance frequencies of the fundamental flexural mode, the longitudinal mode, and the second flexural mode are 1.47 kHz, 7.50 kHz, and 9.77 kHz respectively. The sharp minimum between the longitudinal and second flexural modes is due to the phase difference between these modes.

Clearly, the fundamental flexural mode is more sensitive than the longitudinal mode to changes in hoop stiffness. In particular, when the cork was removed the fundamental resonance frequency decreased by 45% whereas the longitudinal resonance frequency decreased by only 1%. There was also a reduction in the resonance frequency of the second flexural mode from above 10 kHz to 9.77 kHz (note that the TVR sweeps were arbitrarily limited to the frequency range 500 Hz to 10 kHz). We will see a further shift to lower frequencies for the second flexural mode in the next section.

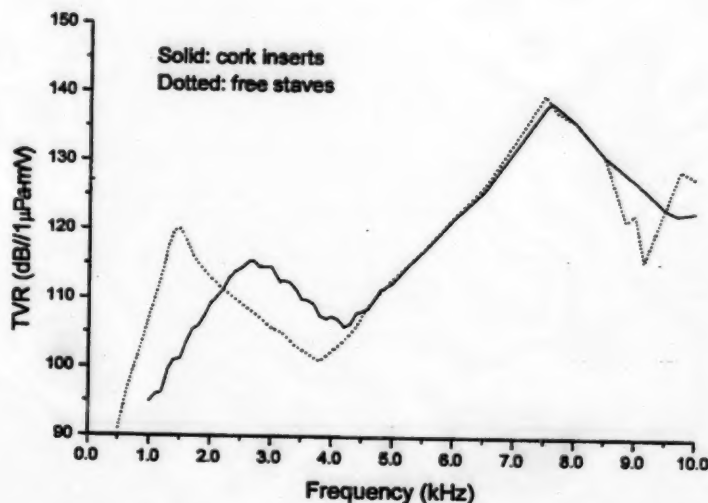


Figure 2: TVR for the transducer with (solid) and without (dotted) cork inserts.

4. Stave Compliance Effects

The thickness, and hence stiffness of the transducer staves was reduced by machining thin layers of metal from the aluminum staves on a tracer lathe. The maximum stave thickness of 6.35 mm was lowered to the following values: 5.59 mm, 4.83 mm, 4.06 mm, and 3.81 mm. The transducer was re-booted and re-tested for each thickness. The measured TVR curves for the 6.35 and 4.83 mm cases are shown in Fig. 3. Note that the 6.35 mm curve also appears in Fig. 2 for the free stave configuration.

Each TVR curve in Fig. 3 has three maxima separated by two minima. The frequencies of these extrema are listed in Table 2, along with the corresponding values for the other three stave thicknesses. The 6.35 mm curve has a fundamental flexural peak at 1.47 kHz followed by a minimum at 3.80 kHz, a longitudinal resonance peak at 7.50 kHz, a steep second minimum at 9.15 kHz, and finally a second flexural peak at 9.77 kHz. The 4.83 mm curve has a lower fundamental flexural resonance at 1.28 kHz due to the increase in stave compliance. What is more noteworthy is that the second flexural peak at 6.25 kHz is now lower in frequency than the longitudinal peak at 7.75 kHz.

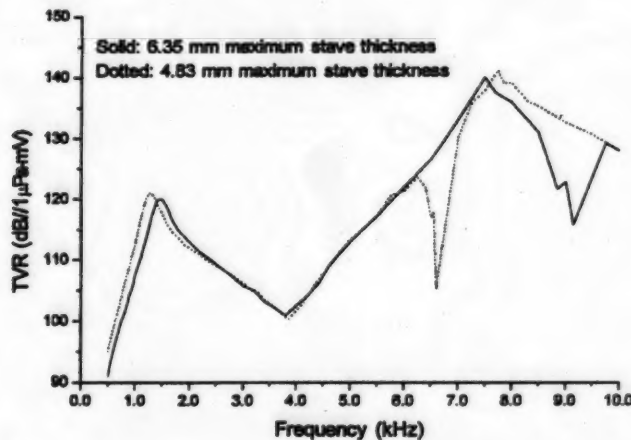


Figure 3: TVR for maximum stave thicknesses 6.35 mm (solid) and 4.83 mm (dotted).

Table 2: TVR extrema frequencies.

Stave Thickness (mm)	Fundamental Flexural Peak (kHz)	First Minimum (kHz)	Second Flexural Peak (kHz)	Second Minimum (kHz)	Longitudinal Peak (kHz)
3.81	1.15	3.80	5.01	5.36	7.51
4.06	1.20	3.84	5.32	5.72	7.50
4.83	1.28	3.84	6.25	6.60	7.75
5.59	1.43	3.86	9.11	8.51	7.31
6.35	1.47	3.80	9.77	9.15	7.50

The data in Table 2 are plotted in Fig. 4 to better illustrate the frequency shifts of the peaks associated with the fundamental flexural mode, the second flexural mode, and the longitudinal mode as a function of stave thickness. These are the solid lines. The shifts in the minima between the peaks are given by the dotted lines.

As the stave thickness (and stiffness) increases from 3.81 to 6.35 mm, the fundamental flexural resonance frequency increases from 1.15 kHz to 1.47 kHz, a significant change of 28%. As well, the first minimum that separates the fundamental flexural mode from the other vibrational modes is essentially constant at 3.80 kHz. The small 1% increase in the frequency of this minimum at intermediate stave thicknesses is due to the shifts in the adjacent modes.

The second flexural mode resonance frequency increases from 5.01 kHz to 9.77 kHz over the same 3.81 to 6.35 mm maximum stave thickness range. This frequency increase of 95% clearly indicates a strong dependence on the elastic properties of the staves.

The longitudinal mode resonance frequency is about 7.50 kHz for both the thickest and thinnest staves reported here. However, it should be pointed out that at intermediate stave thicknesses the second flexural mode and longitudinal mode are closely coupled. Consequently, the peaks in the TVR curves only approximate the actual resonance frequencies of these modes. Therefore, the frequency of the peak associated with the longitudinal mode varies over the intermediate stave thicknesses as shown in the figure. The sharp second minimum always separates the second flexural and longitudinal peaks regardless of the order of the two modes.

Finally, there is a single stave thickness where the frequencies of the second flexural mode, the longitudinal mode, and the second minimum are nearly identical. This crossover point occurs at a frequency of 7.57 kHz and a stave thickness of 5.18 mm. Although none of the stave thicknesses in this study were close to 5.18 mm, a different barrel-stave transducer with a stave thickness of 5.3 mm was also built and tested. Its TVR curve is shown in Fig. 5.

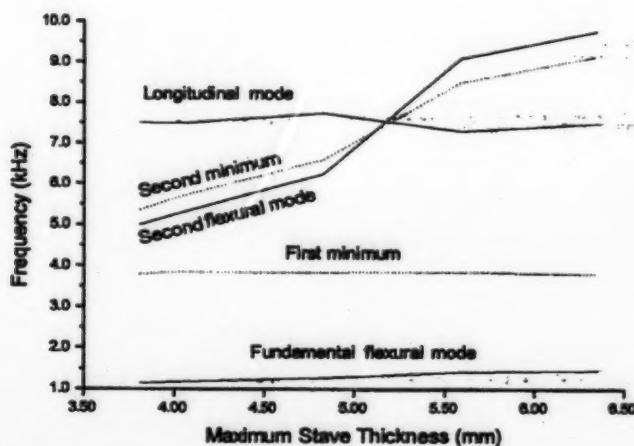


Figure 4: Maxima (solid) and minima (dotted) versus stave thickness.

Interpretation of the frequency range around 8 kHz in Fig. 5 without a priori knowledge of the coupling between the second flexural and longitudinal modes can be confusing. However, with the help of Fig. 4 it is apparent that the second flexural mode and the longitudinal mode have nearly the same resonance frequency with the sharp minimum sitting near the crest.

If a Class I barrel-stave flextensional transducer is designed for use at the longitudinal resonance frequency, it is essential that the crossover point be avoided since the transducer is an inefficient radiator at frequencies near the sharp minimum. However, if a dual-shell Class III barrel-stave flextensional transducer is being designed for broadband applications, it is useful to employ the stave geometry at the crossover point since the longitudinal peak will occur at lower frequencies owing to the greater length of the Class III design. This strategy will ensure that the frequency of the sharp minimum lies above the wide operating band formed by the coupling of the fundamental flexural and longitudinal peaks.

5. Conclusions

The vibrational modes of the Class I barrel-stave flextensional transducer have been studied in this work. It has been shown that the flexural and longitudinal modes can be identified by observing shifts in their resonance frequencies caused by increasing the hoop stiffness of the staves using cork inserts. The increase in hoop stiffness caused significant frequency increases for the flexural modes but did not appreciably affect the longitudinal mode.

By changing the thickness of the aluminum staves it was possible to investigate the coupling between the second flexural mode and the longitudinal mode. For thin, compliant staves the frequency of the second flexural mode fell between those of the fundamental flexural mode and the longitudinal mode. For thick, stiff staves the second flexural mode occurred at the highest frequency. The design significance of the crossover point where the frequencies of the second flexural mode and longitudinal mode were the same was discussed.

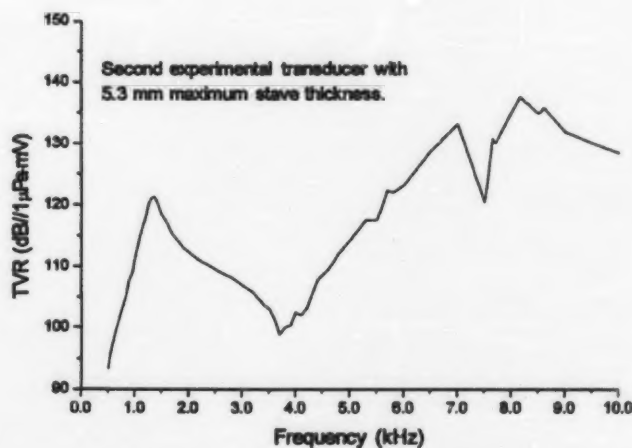


Figure 5: TVR for second Class I barrel-stave flextensional transducer.

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